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# Designing an integrated daylighting system for deep-plan spaces in Malaysian low-rise buildings

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## Abstract

Daylighting technologies have been developed recently to harness solar energy, and eventually, meet the goals of sustainable development. However, the use of natural light in the tropics is challenging. Many factors limit the efficiency of solar energy because of the intensity of solar irradiance and the inconstancy of sky conditions in this region. This research aims to design and evaluate an integrated daylighting system for enclosed spaces without access to daylight from side openings. The proposed system eliminates the requirements for electrical lighting during daytime. The new design combines three components, namely, roof light, dynamic shading, and fiber optic daylighting system, in one integrated platform. The methodology was based on a quantitative approach that used empirical experiments in an actual-sized room. Two stations were set up outside and inside the test cell for data collection. The study used a data acquisition system with nine calibrated sensors to record the performance of the integrated daylighting system. The readings indicated the capability of the system to control natural light from 8:00 to 18:00, even during peak hours. Results showed that the proposed system utilized and boosted the efficiency of the individual components, and the fiber optic daylighting system delivered sufficient level of natural light within the range of 300–680 lux, at an average of 492 lux, with functionality ranging from 44% to 54%. In addition, the skylights were controlled with a dynamic shading system and delivered a maximum reading below 2000 lux during peak times, at an average of 350 lux, with functionality between 46% and 56% under the intermediate sky condition. The integrated daylighting system delivered uniform illuminance when solar irradiance was above 500 W/m$^2$.

**Keywords:** integrated daylighting system; skylight; fiber optic; daylighting; dynamic shading; tropics

## 1. Introduction

Malaysia is a tropical country located in Southeast Asia with a population of 30.7 million, a gross domestic product growth rate of 4.70%/year, an energy independence of 100%, and total carbon dioxide emissions of 7.30 t$CO_2$/capita (Department of Statistics Malaysia, 2015; Enerdata, 2015). The demand for energy of consumers in Malaysia is among the highest in Southeast Asia. Reports indicate that electricity consumption increases significantly each year with 94,666 GWh in 2010, 97,939 GWh in 2011, 102,174 GWh in 2012, and 105,861 GWh in 2013 (Energy Commission, 2015). Clean and renewable energy, such as solar energy, represents only 6 ktoe from a total production of 98,315 ktoe in 2013 (Energy Commission, 2015). Tenaga Nasional Berhad (2015) has reported that the number of electricity consumers in Malaysia is increasing steadily. In the residential sector, the number of consumers reached

6,128,224 in 2009 and 6,710,032 in 2014. In the commercial sector, the number of consumers reached 1,224,414 in 2009 and 1,404,501 in 2014. In general, the building sector is one of the highest energy consumers in the world, accounting for 40% of the total energy consumption globally (Lam et al., 2008; Hassan et al., 2014); this percentage comprises nearly 48% of the electricity consumption in Malaysia (Chua and Oh, 2011). These situations directly challenge the plan of Malaysia to become a developed country by 2020 and to fulfill the requirements of the 2015 United Nations Climate Change Conference held in Paris (COP21) by limiting global warming to below 2 °C.

To achieve sustainable development, electricity consumption should be reduced; hence, the 11th Malaysia Plan for 2016–2020 aims to promote the use of green technology in providing electricity products and services (Kolony, 2011). However, statistics have indicated that the cooling and lighting loads in Malaysian buildings will pose the main challenges. Saidur et al. (2009) reported that lighting in Malaysian office buildings represented approximately 19% of their total energy consumption. Lighting consumption depends on the purpose of the building and the use of daylight (Roshan and Barau, 2016). The energy consumption level depends on the power consumption of lighting systems and the operating periods. The US Department of Energy (2012) indicated that 62% of the residential sector worldwide still uses energy-inefficient lighting systems. Khorasanizadeh et al. (2015) suggested that replacing conventional lighting units with efficient lighting systems in Malaysian buildings could significantly reduce energy use. In addition, they asserted that using lighting technology in certain cases could save energy for up to 50% with minimal or no efficiency loss. The Chartered Institution of Building Services Engineers (CIBSE, 2012) asserted that applying lighting technology could decrease lighting costs by 30%–60% and reduce environmental impact.

Li (2009) and Hee et al. (2015) indicated that energy consumption level would depend mostly on the building envelope, and particularly, on fenestration. BülowHübe (2001) attributed 20%–40% of wasted energy in a building to openings, with the percentage increasing further in tropical countries. Thus, fenestration requires an appropriate design to satisfy the required level and balance of user comfort and energy gain/loss in a building (Li and Lam, 2001; Hee et al., 2015). By 2035, the largest source of carbon dioxide emissions is predicted to be the electricity generation sector (33%), followed by the domestic transport sector (24%), and then the industry sector (21%) (APEC, 2013). Lancashire (1996) specified that each kWh of energy saved would stop the emission of 680.39 g carbon dioxide, 5.67 g sulfur dioxide, and 2.27 g nitrogen oxide. Annual savings in carbon dioxide emissions through the daylighting approach in buildings were estimated to reach 192 million t in 2000 and 223 million t in 2010 (Burton and Doggart, 2000). McHug et al. (2004) asserted that the use of skylight (SL) as a daylighting system could reduce energy demand in the United States by 24,000 MW. Alrubaih et al. (2013) estimated that using daylighting systems could contribute efficiently to overcoming the problem of energy consumption from artificial lighting during daylight and could cut off less than 0.015 USD/kWh throughout the lifetime of a building. Therefore, understanding daylighting can save energy, decrease electric lighting costs, and reduce electricity demand during peak seasons.

## 2. Literature Review

Malaysia is a hot and humid country with a constant climate condition throughout the year. This characteristic creates nearly similar environments for buildings during their life cycle. Studies show that Malaysian buildings are exposed to high levels of solar insolation, which limits and restricts the adoption of passive strategies, particularly daylighting, in low-rise buildings (Al-Obaidi et al., 2014a, 2016a). The highest level of solar intensity ranges from 1750 kWh/m$^2$/year to 1850 kWh/m$^2$/year (Haris, 2010). The majority of sky conditions in Malaysia is intermediate, and cloud cover ranges from 6 oktas to 7 oktas

(Shahriar and Mohit, 2006). Zain-Ahmed (2002) divided sky conditions in Malaysia into intermediate (86% of the time) and overcast (14.0%). Lim and Heng (2016) indicated that daylighting studies in the tropics should consider inconsistent cloud formations of intermediate skies. Zain-Ahmed (2002) specified that illuminance level would exceed 80 k lux at noontime in March but would achieve less intensity (60 k lux) in December. Lim et al. (2012) and Al-Obaidi et al. (2014b) exhibited that global illuminance could reach over 110 k lux with more than 1000 W/m$^2$ on clear days.

Several studies have presented different types of approaches to deliver natural light into deep-plan spaces (Mayhoub, 2014). Nevertheless, the use of toplighting systems in tropical buildings remains challenging, particularly in low-rise buildings (Rahman et al., 2013). A survey conducted on different types of daylighting systems found that the SL system could be extremely useful. However, harnessing SL for low-rise building in this region is difficult and requires complex modification to control the effects of heat gain, light level, and solar intensity in indoor spaces, which can cause thermal and visual discomfort (Chel et al., 2010; Yunus et al., 2011; Al-Obaidi et al., 2014a, 2015). Christopher (2009) suggested the fiber optic daylighting system (FODS) as a viable solution. However, the application of FODS was found to be limited in this region because of the inconstancy of sky conditions (Abdul-Rahman and Wang, 2010; Munaaim et al., 2014a, 2014b). Furthermore, studies have shown that shading devices remain under research in this region due to constraints in sunlight quantity, i.e., direct and diffused sunlight (Al-Tamimi and Fadzil, 2011; Lim et al., 2013; Lim and Heng, 2016). Therefore, this section reviews several strategies used in SL systems, FODSs, and daylight control systems (DCSs) to understand their potential for integration.

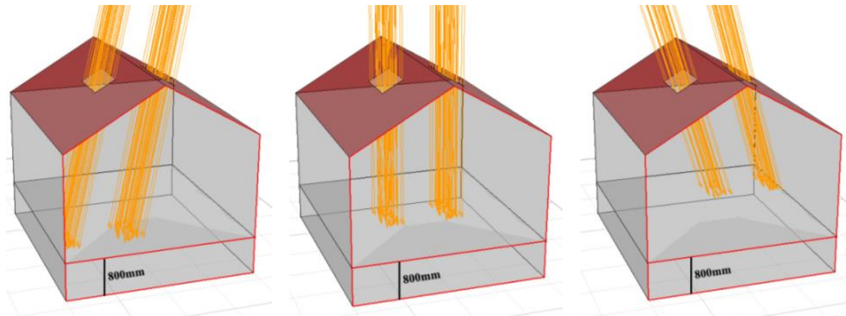
## 2.1. Skylight Systems (SL)

Skylight is a special fenestration element that delivers a uniform level of illumination over an interior space. However, its performance varies under different sky conditions and solar intensities (McHug et al., 2004; Al-Obaidi and Rahman, 2016b). Al-Obaidi et al. (2014a) conducted a conceptual study to evaluate the behavior of solar radiation in the form of light and heat that fell upon, interacted with, and was emitted from an SL system in a single-story building. Their study identified a process that classified independent and dependent variables with different natural loads. Several studies were also conducted to identify the optimum SL model. In the US, Lee et al. (1996) introduced a system with four elements: a skylight opening, a lightwell, a reflector array, and a lower diffusing panel. Their study found that the system enhanced light distribution by controlling and reflecting direct sunlight through a prismatic film. In Peru, Beltran (2005) studied different configurations of daylight parameters using various diffusing materials and reflectors in several types of SL systems. The results indicated that using reflectors enhanced the distribution and uniformity of light in spaces. In India, Chel et al. (2010) investigated different types of traditional SL systems in pointed roofs using mathematical models compared with the CIBSE prototype. The results identified different daylight factors and illuminance levels at various vertical levels. In South Korea, Kim and Chung (2011) conducted a study on different types of toplight systems by implementing 20 scaled prototypes with a lightwell and different reflectance values in indoor elements against currently available SL systems. The study found that a monitor SL could provide effective performance in cutting direct sunlight, whereas a sawtooth SL could exhibit stable performance in light distribution. In Malaysia, Yunus et al. (2011) tested SL systems in different roof shapes, such as flat, structured pyramidal gridded, sawtooth, and pitched roofs. The results showed different findings, such as high angles, complicated roof profiles, east-facing and west-facing surfaces, and the decrease in daylight level to over 50%. In Turkey, Yildirim et al. (2012) studied five SL systems for roofs, namely, a single-layer one-way roof SL system, a single-layer two-way roof SL system, a sunshade with double layers, a double-layer system without sunshade, and a moving sunshade with double layers. Their research showed that a moving sunshade with double-layer roof system distributed uniform and sustainable lighting under all conditions compared with the other four SL systems.

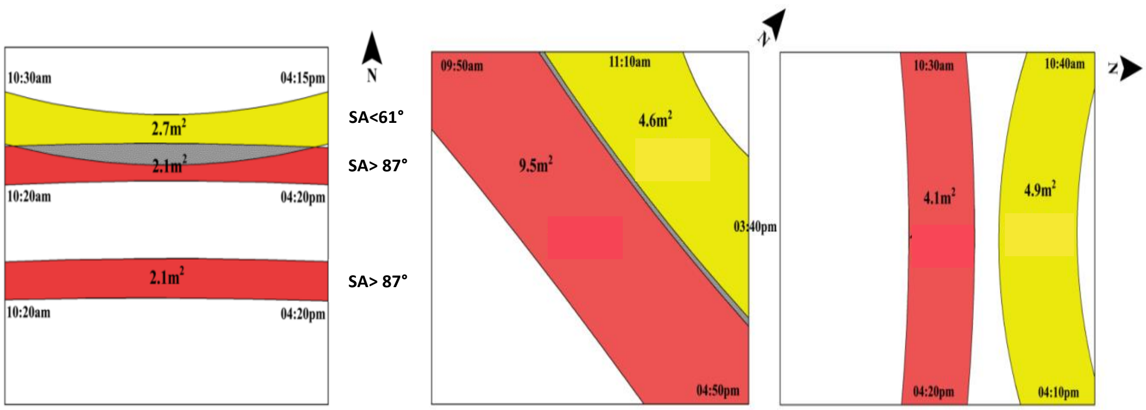
Acosta et al. (2013) analyzed the performance of lightwell SLs under overcast sky conditions. They investigated different variables of SLs, including size, height/width ratio, reflection index, and spacing, as well as the height, width, and length of a room. The model used in the study represented the typical dimensions of a museum or library room. Although limited to the analysis of the daylight factor, this study tested different parametric designs of SLs with variable heights, such as lightwell SLs with dimensions of 1.00 m × 1.00 m, 1.50 m × 1.50 m, and 2.00 m × 2.00 m. The results show that the size of an SL system is inversely proportional to the height of the reflectors. Therefore, when maintaining height/width ratio, doubling the size of an SL will produce approximately twice the illuminance. Furthermore, Acosta et al. (2015) investigated the performance of monitor SLs under overcast conditions. They identified an appropriate proportion and shape for monitor SLs to maximize illuminance on the workplane within a room. The study tested the performance of the SLs in a model with the typical dimensions of a museum or library room, i.e., 9 m (length) × 9 m (width) × 4.5 m (height). The monitor SLs, which were 6 m long and had variable heights and widths, were each inserted into the center of the roof. Similar to their earlier research, this study only considered the daylight factor. The targeted shapes were rectangular, slanted, sawtooth, and curved monitor SLs. The results showed that the highest daylight factors could be observed in the roof with monitor SLs with a height/width ratio close to 1/1, regardless of reflector shape and room ratio. Moreover, the slanted shape performed better than the other shapes. The performance increased by up to 4.00% when the height/width ratio was 1/5.

A suitable design for an SL system can help utilize natural light properly. Many factors affect SL design, such as size, glazing type, orientation, placement, and shading amount. Oral (2004), Part and Safety (2007), and Szokolay (2008) discussed factors that must be considered when selecting glazing materials. Glazing materials generally transfer a significant amount of heat and light through the system. Al-Obaidi et al. (2014c) specified factors for evaluating the characteristics of glazing materials. They identified two categories of SL materials: glass and plastic materials. Glass materials include clear glass; tinted glass; wavelength selective coating; insulated glass; electrochromic, thermochromic, and photochromic glasses; laminated glass; wired glass; and vacuum glass. Plastic materials include glass-reinforced plastic, polyvinyl chloride, polycarbonate, acrylic, fiberglass, and copolyester. Plastic can provide a good medium for SL systems due to the high cost of glass materials. Polycarbonates comprise a specific group of thermoplastic polymers that are applied extensively as an SL glazing material and exhibit excellent thermal insulation with a transparent medium that controls excessive illuminance levels (National Association of Rooflight Manufacturers, 2009). Polycarbonates are 100% recyclable and can eliminate 99% of ultraviolet radiation (Bristol Daylighting Systems, 2013). Mintorogo (2007a and 2007b) studied the effects of polycarbonates on an SL system with horizontal or sloped SLs in tropical climate. Mayhoub (2014) and Gong et al. (2016) suggested that glazing materials could be improved in three steps. First, a glazing material alters itself by changing its chemical composition or physical characteristics. Examples are tinted glazing, aerogel, and chromogenic glass. Second, a coating, such as a microscopically thin, low-emissivity coating, is applied to the surface of a glazing material to reduce heat gain and glare. Third, various layers of glazing are assembled, and the properties of the spaces between them are controlled. Bojic and Yikb (2007) investigated the relationship of different types of glazing materials for windows to energy in residential buildings. They found that low-emissivity glass, double-glazed glass, and clear glass windows with low emissivity reduced power consumption by up to 4.2%, 3.7%, and 6.6%, respectively.

Al-Obaidi et al. (2014b; 2015a; 2015b) studied the performance of SLs in Malaysian environment through simulation and empirical models. The studies were conducted in a room with dimensions of 5 m (length) × 4 m (width) × 3 m (height). The results showed that different impacts and paths in the indoor environment were created each month, as shown in Figure 1. The SL in 45° orientation produced the widest area for direct sunlight, with a maximum of 9.5 m2 in April (SA> 87°) and 4.6 m2 in January (SA<61°). This orientation also exhibited the longest path during daytime from 10:30 to 16:30. However, the 0° orientation generated the thinnest area with 4.2 $m^2$ in April and 2.7 $m^2$ in January. The SL in 90° orientation produced a small area of direct sunlight in April with the shortest time, i.e., from 10:30 to 16:20.



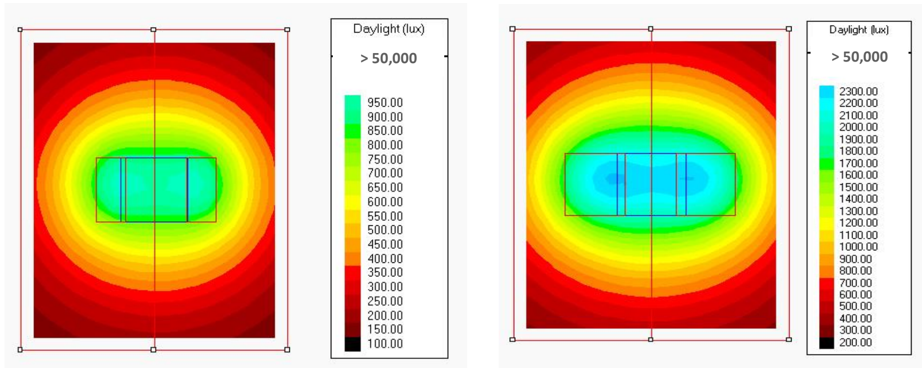

(a) Example of sunpath beahviour with 45° orientation in April




(b) Location and area of light beam for 0°, 45°, 90° orientation (Minimum SAT< 61º and Maximum SA> 87º)

Figure 1: Direct sunlight paths and areas for building with 0°, 45°, and 90° orientations (Al-Obaidi et al., 2015a)

Al-Obaidi et al. (2015a) also compared the performance of polycarbonates against other glazing materials, such as single glass, double glass, double low-emissivity glass, single polycarbonate, and double polycarbonate. Their study found that double polycarbonate provided an effective and optimum SL material. The research also tested the sizes of SL materials under intermediate sky condition. The results showed that an SL measuring 1 m × 0.5 m produced illuminance levels according to the target range compared with an SL measuring 1 m × 1 m. The study also found that the maximum daylight factor was 3.30% with the 1 m × 0.5 m SL. Moreover, the illuminance was 983 lux compared with that in the 1 m × 1 m SL, where the daylight factor was 7.90% and the illuminance was 2322.88 lux. Figure 2 shows the daylight analysis of the two different SL sizes at a height of 800 mm from the floor during the highest altitude of the sun on April 1 at 13:30 with over 50,000 lux recorded outside. Al-Obaidi et al. (2014b) empirically assessed the performance of SLs with polycarbonate materials. They designed a special rooflighting system with a specific component in the SL to diffuse and reflect natural light in two layers. This component controlled the properties of the spaces between the layers. The study was conducted in two stages. The first stage evaluated the condition of only the skylight system without a ceiling. The second stage was designed to have a transparent ceiling (TC), as shown in Figure 3.




Skylight size 1m x 0.5m

Skylight size 1m x 1m

Figure 2: Daylight analysis of two SL sizes (Al-Obaidi et al., 2015a)


Figure 3: Application of SLs without transparent ceiling and SLs with transparent ceiling under the Malaysian sky condition (Al-Obaidi et al., 2014b)

The research was conducted during clear days. Outdoor illuminance was recorded at over 110 lux during peak times when the sun was perpendicular within the altitude of 89° between March and April. The study found that the system produced an excessive amount of illuminance during the first stage. The reading reached a maximum value of approximately 33963 lux in an indoor environment with direct sunlight. However, when the SLs were integrated into a transparent ceiling, a maximum of 20850 lux was reached in an indoor environment exposed to direct sunlight. The results showed that the system could deliver illuminance below 2000 lux during daytime with a minimum of 82.61% and a maximum of 86.96% during the peak dates of the year. However, this study did not overcome 14%–17% excessive direct sunlight during the peak season. This excessive illuminance level occurs between 11:00 and 14:00. Therefore, overcoming this issue is critical.

## 2.2. Innovative Daylighting Systems (IDS)

Innovative daylighting systems have different types that utilize solar energy to transfer natural light to remote and windowless spaces in buildings to maximize the use of available daylight. The structure of these systems consists of a light collector, a light guide, and a diffuser, with the possibility of combining two of these components in one part (Vu and Shin, 2016). The light collected in these systems is transferred through fiber optics or light pipes (ducts) with highly reflective materials for transmittance, which exceed 99% per light bounce (Whitehead et al., 2009; Kennedy and O'Rourke, 2015). These systems function through passive or active collectors installed on the building roof or attached to the building façade (Song et al., 2015). Mayhoub (2014) identified different types of innovative daylighting systems, which are mostly light ducts and fiber optic systems, as shown in Table 1.

Table 1: Application of innovative daylighting systems in buildings (Mayhoub, 2014)

| **IDS** | **Collector location** | **Light guidance media** | **Building form** | **Delivery potential limit** | **Delivery favorable limit** |
|---|---|---|---|---|---|
| **TDGS** | Roof | Light duct | Deep-plan | Up to 40 m | Unlimited[a] |
| **Heliobus** | Roof | Light duct | Multi-storey | | Up to 5 stories |
| **Himawary** | Roof | Fiber optics | Deep-plan | Up to 200 m | N/A |
| **Parans** | Roof | Fiber optics | Deep-plan | Up to 20 m | Up to 10 m |
| **Sundolier** | Roof | Light duct | Deep-plan<br>Multi-storey | | Unlimited[a]<br>Upper 3 stories |
| **Sunportal** | Roof | Light duct | Deep-plan | Up to 200 m | N/A |
| **SunCentral** | Roof | Light duct | Multi-storey | | Unlimited storey/up to 15 m depth |
| **HSL** | Roof | Fiber optics | Multi-storey | Upper 5 stories | Upper 2 stories |

[a] Using as many units as required.
N/A: not available

These systems have a similar function to that of SLs, which utilize direct and diffused sunlight for a light tube, whereas only direct sunlight is used in FODSs. However, both of these systems have limitations, i.e., they require clear skies and a continuous supply of sun rays during the day to function (Munaaim et al., 2014a). Christopher (2009) indicated that incorporating a lighting strategy into natural light remained a complicated procedure. Several factors affect daylighting systems, such as intensity, variability, and thermal load associated with sunlight. This issue can lead to a serious concern in terms of user comfort, such as attenuating or controlling direct sunlight.

Different studies have found that the use of a light duct is limited due to the rigidity and permanent position of pipes when channelling light from the outside inside a building (Andre and Schade, 2002). However, Abdul-Rahman and Wang (2010), Nabbu et al. (2011), and Munaaim et al. (2014a; 2014b) argued that fiber optic represents one of the promising techniques in daylighting. Sansoni et al. (2008), Abdul-Rahman and Wang (2010), Patrick et al. (2011), and Irfan and Seoyong (2012) identified problems and offered suggestions. Ullah and Shin (2014) investigated the performance of optical fibers in delivering uniform light to large-scale building interiors. This study used two approaches: the parabolic trough and the linear Fresnel lens. It was conducted in an office building at 12:30 and both daylighting systems were presumed to have sun-tracking devices to rotate the light-collecting modules. The system was illuminated via collimated light. The results showed that some readings exceeded 1600 lux (Figure 4). Moreover, using a hybrid approach by combining sunlight and LED light with electric lighting can maintain an average level of 500 lux and reduce energy consumption. Vu and Shin (2016) presented a cost-effective optical fiber daylighting system composed of modified compound parabolic concentrators (M-CPCs) coupled with plastic optical fibers. They used LightTools™ simulation to design the geometric form of the M-CPCs. The simulation results indicated that 84% optical efficiency was achieved. This approach helps in using a low-accuracy sun tracking system as a cost-effective solution. The researchers also found that the maximum illuminance level was 560 lux.

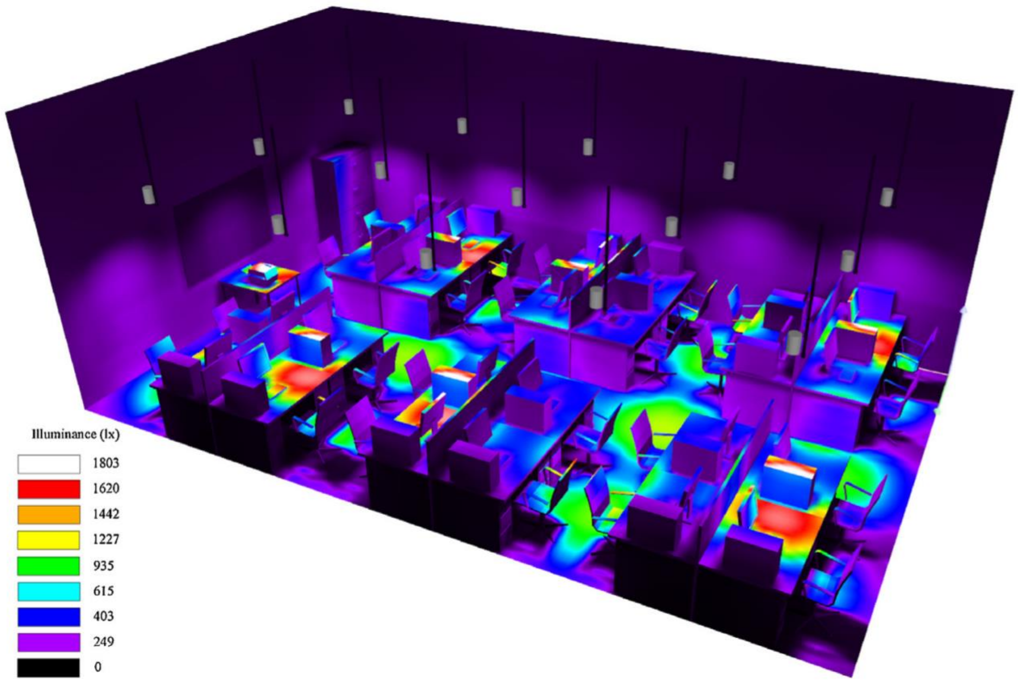



Figure 4: Simulation of the daylight illuminance distribution at the test site (Ullah and Shin, 2014)

Munaaim et al. (2014b; 2014c) investigated the performance of an FODS under Malaysian sky condition. They used the Parans system to test the actual performance of the daylighting system and investigated the passive generation of the Parans model. The systems were tested under three types of sky conditions: intermediate blue, intermediate mean, and overcast. The model SP3 of FODS with a 10 m cable was used on a full-scale test bed model in Penang, Malaysia as an empirical approach. The readings showed that the system was 79% active under an intermediate blue sky with a maximum illuminance of 725 lux and 48.50% active under an intermediate mean sky with a maximum illuminance of 685 lux. However, it was only 37.47% active under an overcast sky with a maximum illuminance of 538 lux. They concluded that the system could deliver over 75% of average indoor illuminance above 300 lux. However, the limitation of this system is that the most dominant sky condition in Malaysia is the intermediate mean sky, which occurs approximately 66% of the year. Hence, the system can only be active 40%–55% of the time. Therefore, buildings in Malaysia cannot rely solely on this approach, as shown in Figure 5.

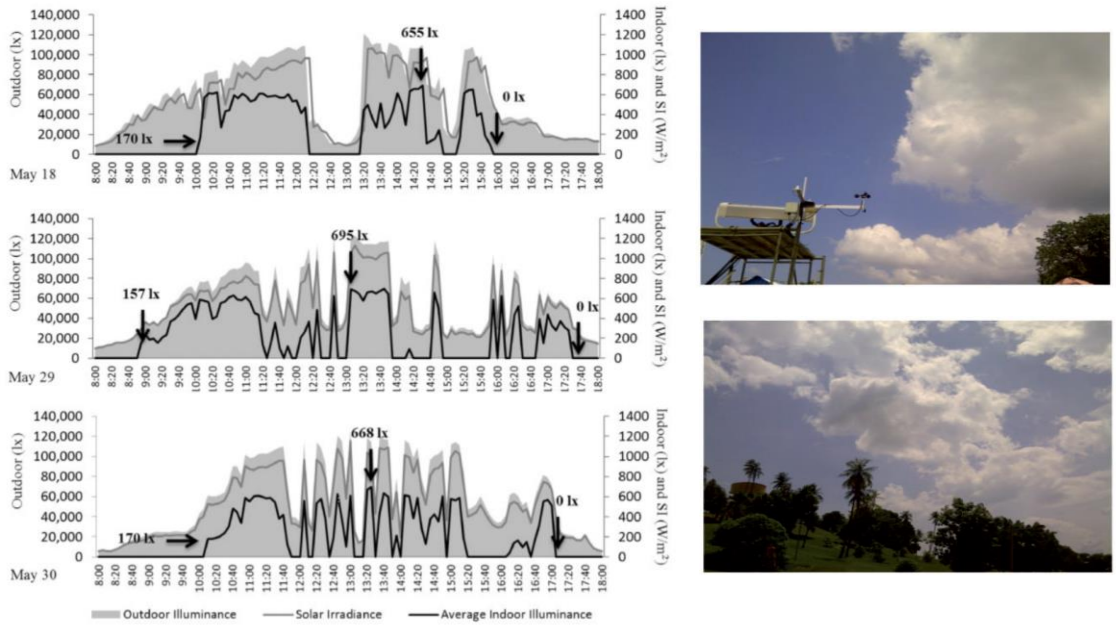
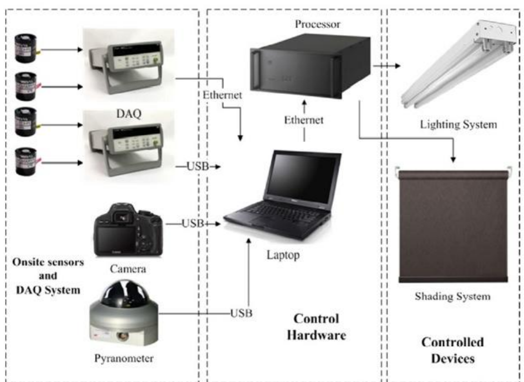



Figure 5: Comparison results of FODS under intermediate mean sky condition in Malaysia (Munaaim et al., 2014b)

## 2.3. Daylight Control Systems (DCS)

DCS represents a model that controls the performance of artificial lighting systems by regulating and dimming light level to save energy (Delvaeye et al., 2016). This system depends on *photosensor* detection to operate (Bellia et al., 2016). Park et al., (2014) described this system as a dynamic approach to diffuse and control the level of natural light in an indoor environment. Several studies have investigated this approach, such as Chaiwiwatworakul et al. (2009), Park et al. (2011), Caicedo et al. (2014), Choi et al. (2016), Kontadakis et al. (2016), and Bellia et al. (2016). Delvaeye et al. (2016) investigated the performance of DCS based on global horizontal irradiance, interior horizontal illuminance, the central programmable logic controller (PLC) system, and several types of terminals connected via EtherCAT to the PLC; power and energy consumption were measured using electronic single-phase energy meters. Choi et al. (2016) investigated the accuracy of the prediction of energy savings using a daylight-responsive dimming system. The study examined the concept of “indirect illuminance” by predicting the potential of lighting energy savings. Rossi et al. (2015) introduced a system that integrated personal control with occupancy and daylight adaptation into a lighting system with multiple luminaires. They used a sensor-driven lighting control and conducted simulation to evaluate the proposed control algorithm. However, this study was limited due to the design of the personal control algorithms and the performance evaluation via simulations. Park et al. (2014) introduced another study to solve the problem of deep building layouts in the US. They integrated a millimeter-scale fluidic channel system with a thinly cast transparent polydimethylsiloxane-based deformable array of louvers and waveguides. Their study presented a dynamic DCS that used fluid inside its channels. Xiong and Tzempelikos (2016) designed a model that combined shading and lighting controls, as shown in Figure 6 (a). This study used model-based control algorithms to obtain satisfying glare constraints and reduce the lighting energy used in office spaces. However, this study used only annual simulation to evaluate its functionality.

Karlsen et al. (2016) developed a solar shading control strategy for venetian blinds in Denmark under a cold climate. This study was conducted in office buildings and used a control strategy based on a combination of internal and external shading devices. The study demonstrated promising performance in controlling solar shading during both winter and summer. Moreover, this study set a value to avoid a vertical illuminance of >1700 lux at the sensor placement by controlling the angles of solar shading (Figure 6 b). Lim and Heng (2016) tested the application of a dynamic internal light shelf in high-rise office buildings in Malaysia. This study used a scale model for validation, and most of the investigation was performed via simulation using software from Integrated Environmental Solutions Ltd. for verification under Malaysian sky condition. The study targeted intermediate sky condition for validation. It identified specific design models. However, the mechanism for control and operation should be further developed. In general, the presented systems are mostly designed to regulate lighting levels and energy consumption by controlling the amount of required daylight in window systems.



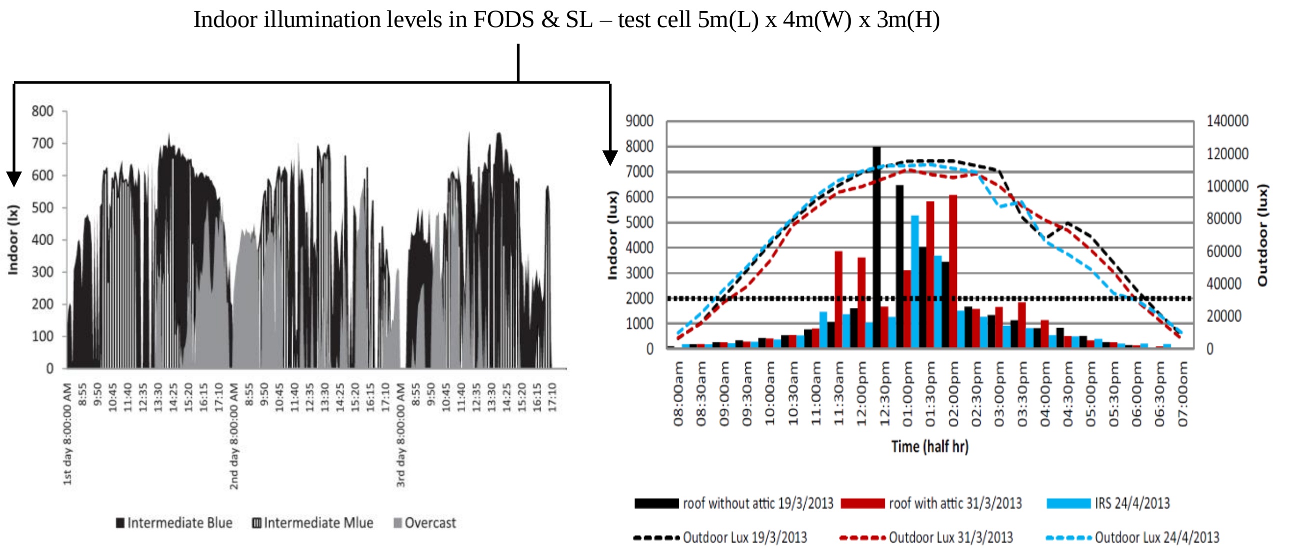

(a) Components and connections of data acquisition and control hardware (Xiong and Tzempelikos, 2016)

(b) Test cells with and without activated external solar shading (Karlsen et al., 2016)

Figure 6: Optimizing control strategy for dynamic shading systems

Generally, the aforementioned studies fail to overcome the issue of direct sunlight, which can occur in SL systems, and its application in the tropics. A summary of the literature review identifies the issues that must be considered in designing a new integrated system. The present work aims to overcome the problems in the Malaysian built environment, as shown in Figure 7. These problems have been identified in the following studies.

- Al-Obaidi et al. (2014b) showed that the illuminance levels obtained from the innovative rooflight system were 82%–86% below 2000 lux. However, the system did not overcome excessive direct sunlight around midday during peak season, which was approximately 14%–17%.
- Munaaim et al. (2014b) investigated FODS using the Parans system. The study found that FODS was affected by different sky conditions that could not provide constant natural light. The system failed to function continuously from morning to evening, particularly when solar irradiance was below 500 $W/m^2$.
- Lim and Heng (2016) tested the application of a dynamic internal light shelf in high-rise office buildings. However, the system was applied only to windows. The study did not develop a mechanism for controlling and operating the dynamic shading system (DSS).




(a) Illuminance levels from FODS (Munaaim et al., 2014b)

(b) Illuminance levels from Rooflight (IRS): skylight + transparent ceiling (Al-Obaidi et al., 2014c)

Figure 7: Illumination levels in developed rooflighting system and FODS in the tropics

## 3. Methodology

The proposed system has been developed based on the limitations of three systems in the Malaysian environment: rooflighting system (SL + transparent ceiling), FODS, and DSS. Therefore, this study investigated the integration of these three systems through different sets of experimental tests. The research adopted a quantitative approach to evaluate the illuminance level in an indoor environment. An empirical method was applied to provide accuracy. This integrated system was tested in a test cell size (5 m × 4 m × 3 m) using the same scale in Munaaim et al. (2014b) and Al-Obaidi et al. (2014b) at 5° 3′N latitude, 100° 3′E longitude inside the main campus of Universiti Sains Malaysia, Penang, Malaysia to maintain the reliability of results. Penang lies in an area that receives a higher level of solar radiation compared with other parts of Malaysia (Haris, 2010). The test bed was built using conventional construction techniques. It had a concrete floor slab, plaster brick walls (white paint) with no window, plaster boards for ceiling, and a corrugated metal pitch roof painted black on the inside to reduce glare and light reflection. The test cell was located in an open area, with nearby buildings (one-story height) and trees located within a distance of approximately 10 m. Sun rays have never been obstructed by any of the surrounding elements; hence, the building receives direct solar rays throughout the day and year.

The proposed integrated daylighting system was developed based on several empirical tests and previous literature to validate its parameters. The design of the DSS was based on the readings provided by Munaaim et al. (2014b), who indicated that FODS would function efficiently when the level of outdoor solar radiation was approximately 500 W/m$^2$ or higher. Al-Obaidi et al. (2014c) indicated that the indoor illuminance level obtained from the innovative rooflighting system exceeded 1000 lux when the system was exposed to over 500 W/m$^2$ of outdoor irradiance. On the basis of these findings, a DSS can be operated only when outdoor solar radiation is over 500 W/m$^2$. Therefore, the present study integrates DSS into SLs to block their function when the system receives over 500 W/m$^2$ and open the SLs when solar level is below the reference point. Figure 8 shows the concept of the proposed system.

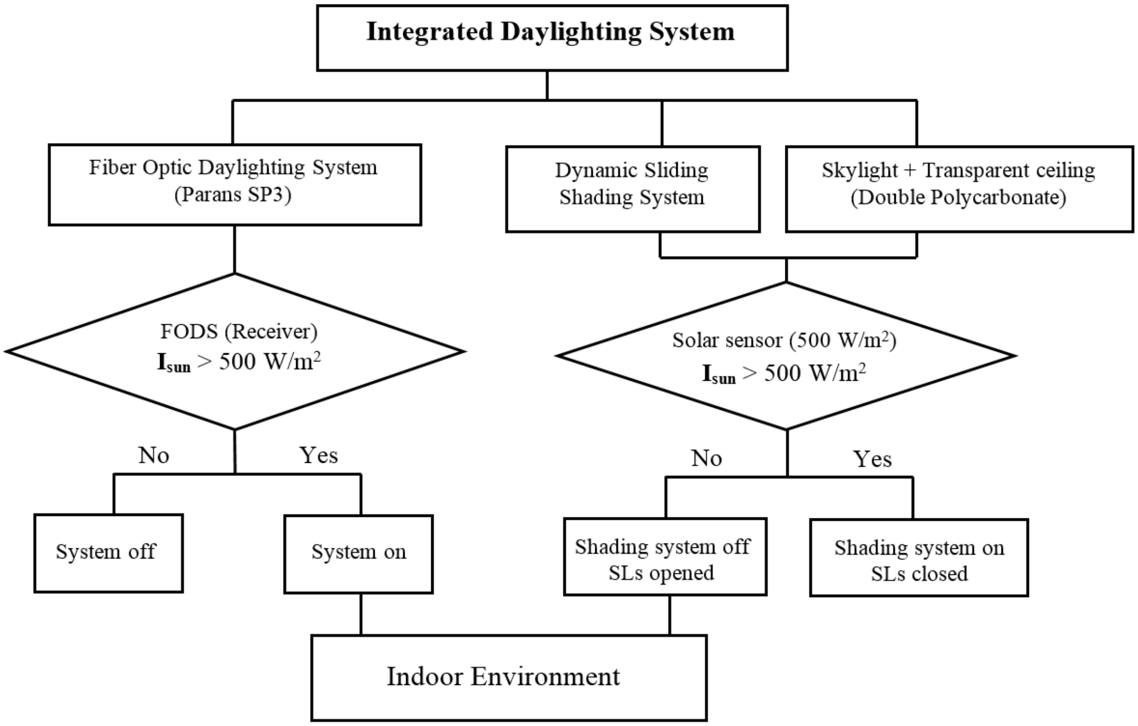



Figure 8: Proposed model of the integrated daylighting system

O'Brien et al. (2013) studied the operation of window shade patterns and identified shade position metrics. Two main metrics are consistently used: mean shade occlusion (MSO) and shade movement rate (SMR). The former identifies the percentage of closing for some group of windows, whereas the latter specifies the speed of movement of shades between two discrete time points (i.e., open and close).

$$\mathrm{MSO}_t = (1/n)\sum_{i=1}^{n}(p_i)_t, \quad (1)$$

$$\mathrm{SMR}_t = (1/n)\sum_{i=1}^{n}(N_i)_t, \quad (2)$$

$$(N_i)_t = countif\left(\frac{dp_i}{dt} \neq 0\right), \quad (3)$$

where *n* is the total number of windows, *p* is the percentage of closed shade *i* at time step *t*, and *N* is the number of shades moved between time steps.

The components of the proposed integrated daylighting system are shown in Figure 9. They include

- Two SLs/double polycarbonate (1 m × 0.5 m) on two sides of a pitched roof (20 $m^2$);
- Transparent ceiling/double polycarbonate (4 m × 2 m) + plaster gypsum board;
- Pitched roof at an angle of 30° and orientation of the test cell at an angle of 45° (northeast);
- FODS (Parans, SP3), Fresnel lenses (receiver: 1140 mm × 570 mm × 270 mm; operating temperature: −20–40 °C; light output: 5500 ± 300 lm at 100,000 lux) with a sunlight tracker, 10 m fiber optic cable (six cables; fiber optic diameter: 7 mm; material of fiber optic: acrylic; light transmission: 95, 5%/m, light spreading angle), and six light diffusers made of acrylic material (450 mm × 450 mm × 90 mm) with a light output of 550 lm;
- Two dynamic sliding shading systems that consist of an aluminum frame, a sliding frame, plywood panels, a DC motor (speed: 0.8 m/sec), a circuit breaker with a PLC device, a pyranometer, and a 50 W solar panel with battery.

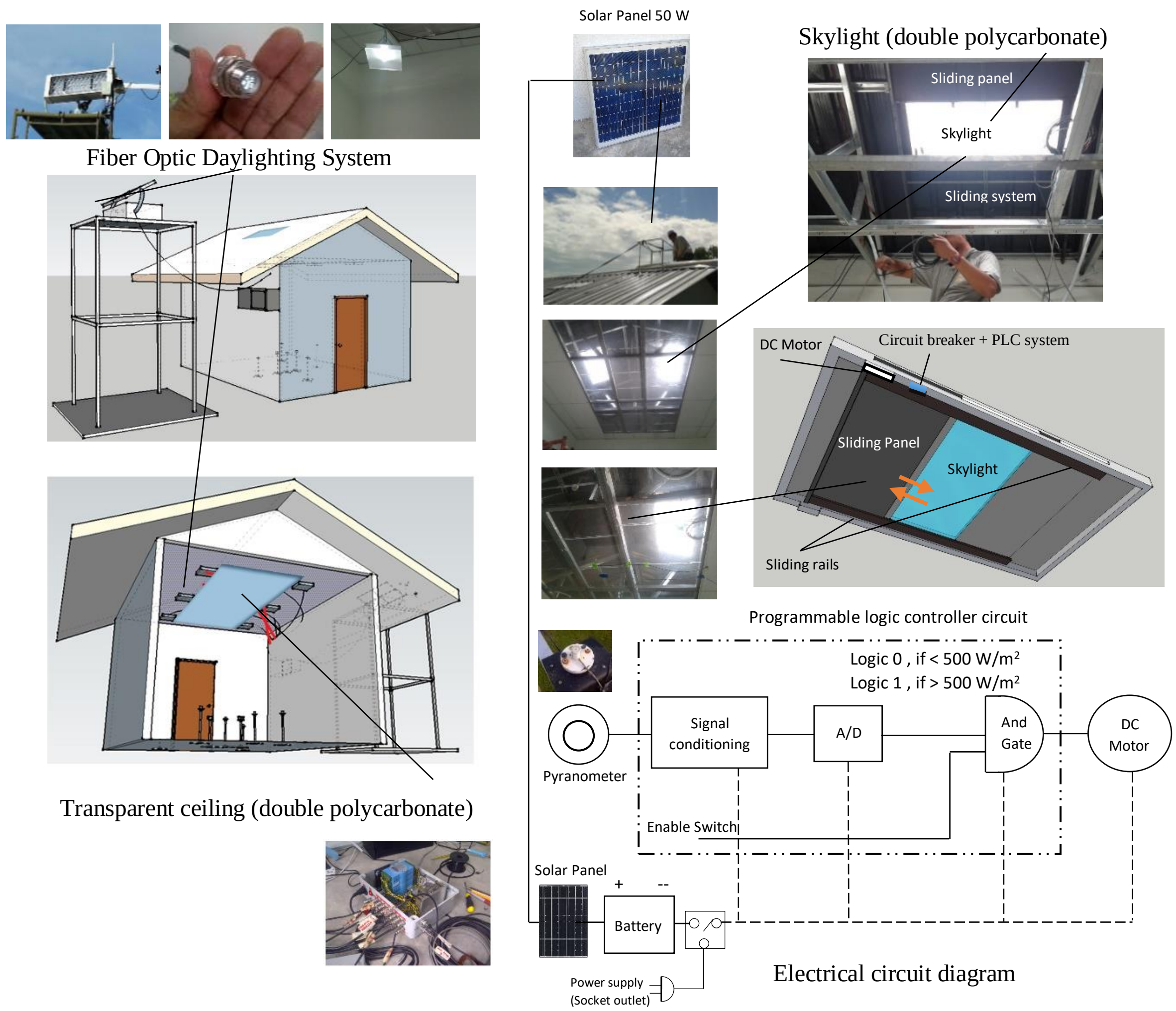



Figure 9: Proposed model of the integrated daylighting system

Two monitoring stations were set up: an outdoor station, which consisted of solar radiation sensors with an outdoor illuminance sensor, and an indoor station with five illuminance sensors (Figure 10). The criteria were based on optimization studies conducted by Munaaim et al. (2014a), Munaaim et al. (2014b), and Al-Obaidi et al. (2014c), which increased the reliability of the present work. The sensors were connected to a data acquisition system for measuring electrical and physical data with a computer for recording and monitoring. The outdoor station was located 3 m above the ground, which was the same height as the SLs and the FODS receiver. The indoor illuminance sensors were positioned 800 mm above the ground to represent the height of the work plane (GBI, 2011); each sensor was placed 1 m from the walls to maintain their accuracy and reduce the effect of reflection. Three main factors were tested: outdoor illuminance, indoor illuminance, and solar irradiance.

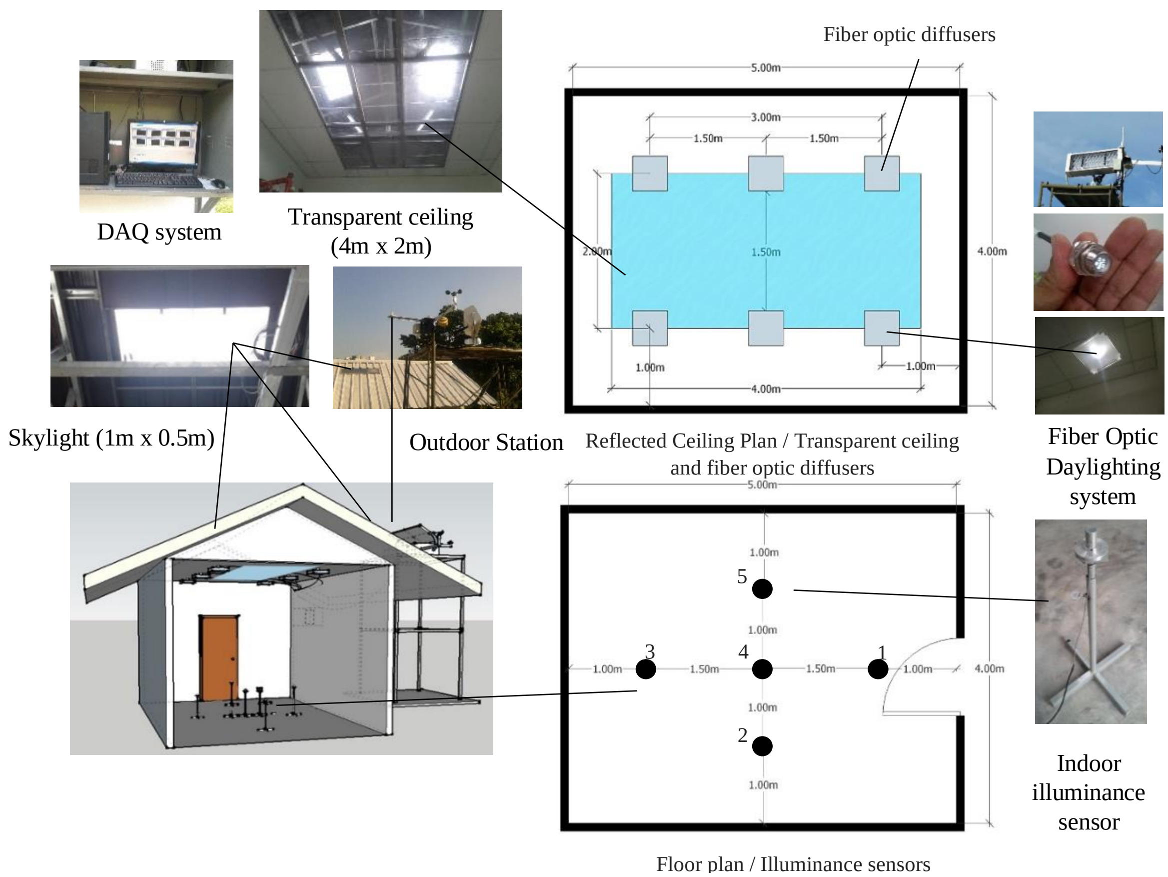



Figure 10: Schematic of the field study measurement setup with the test bed and measuring points

For outdoor and indoor illuminance, this study used Reinhardt ranges from 0 lux to 150,000 lux, Li-Cor #Li-200SA (a solar radiation pyranometer) sensor range of 0–3000 W/m$^2$, and an accurate maximum deviation of 1%. The research was conducted in 2015 during the peak season when the location of the sun reached its maximum altitude of 89° between March and April. The study was conducted for two months from 08:00 to 18:00, and the interval time for data collection was 5 min. The data presented in this paper represent three to five typical days, as indicated in several studies conducted in a similar environment (i.e., hot and humid), such as the field studies of Khedari (2002), Ismail (2010), Ong (2011), Al-Obaidi et al. (2014c), Munaaim et al., (2014b), Al-Obaidi et al., (2014e), and Lim and Heng (2016). The present work followed the nebulosity index to identify its categorizations according to Baker et al. (2013), who calculated the index from the hour ratio of diffuse to global irradiance ($C_r$) as follows:

$$C_i = (1 - C_r)/[1 - 0.12(\sin \varphi_s)^{-0.82}], \tag{4}$$

where
$C_i$ is the nebulosity index,
$C_r$ is the hour ratio of diffuse to global irradiance, and
$\varphi_s$ is the solar altitude.

The three days represent the classification of three different sky conditions: normal typical sunny day with intermediate blue sky (nebulosity index: 0.70<0.95), intermediate mean sky (nebulosity index: 0.20<0.70), and intermediate overcast sky (nebulosity index: 0.05<0.20); these three types of sky conditions account for approximately 86% of sky conditions in Malaysia (Zain-Ahmed, 2002; Munaaim et al., 2014b). The present study applied a statistical analysis to assess system performance through a simplified comparison of the average values of the maximum, mean, and minimum illuminance; these values were further tested through regression and correlation analyses to increase the validity of system performance (Li et al., 2006; Pattanasethanon et al., 2007; Munaaim et al., 2014b). The present study is also divided into two stages (Figure 11). The first stage evaluated the model components and the performance of the shading system with SLs to ensure the reliability of the validation. The second stage tested the model after it was fully integrated. The results were obtained under different sky conditions to reflect the reliability of the system under Malaysian sky conditions: intermediate blue sky (nebulosity index: 0.74), intermediate mean sky (nebulosity index: 0.33), and intermediate overcast sky (nebulosity index: 0.16). Three days were presented to show the performance of the final integrated daylighting system.

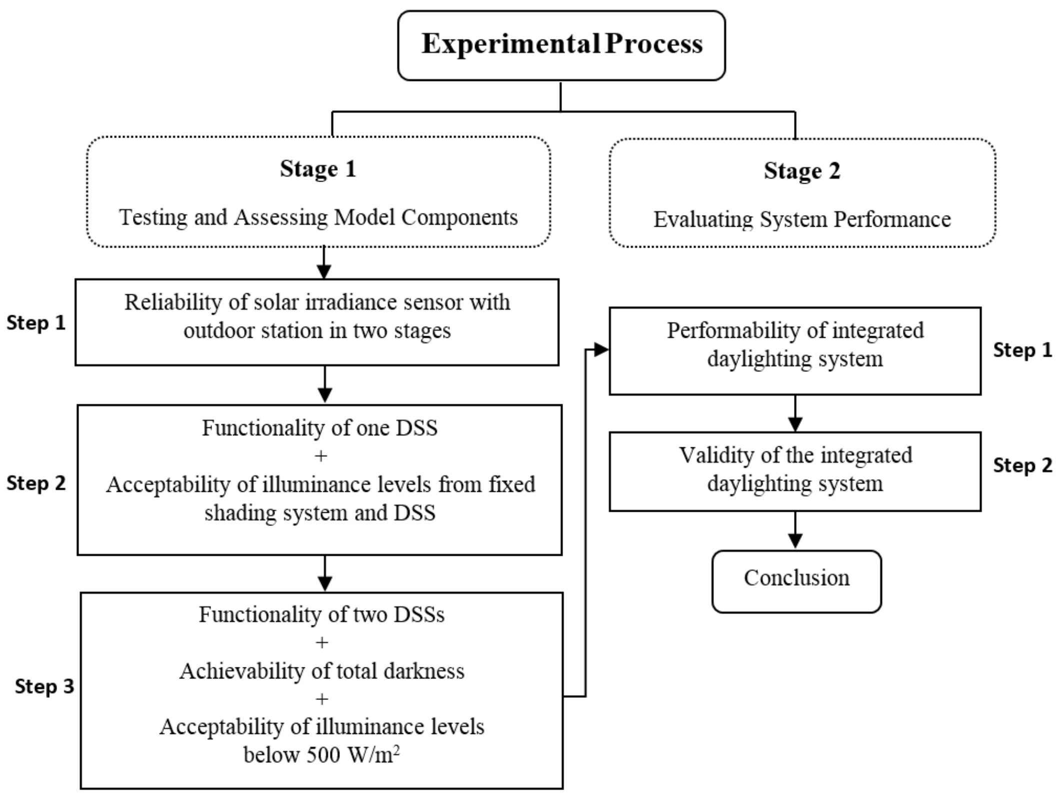



Figure 11: Experimental process of the research

## 4. Results and analysis

### 4.1. First stage

This stage was conducted using three steps. The first step involved testing the reliability of the pyranometer solar radiation sensor connected to the DSS with the outdoor station. The second step involved testing the performance of one DSS in a selected SL while the second skylight was opened. The third step involved investigating the two DSSs to ensure their functionality and reliability to obtain the total darkness condition when the DSS was active. The roof consists of an SL and a transparent ceiling (double polycarbonate) for each part of this stage. Figure 12 shows the regression analysis of the correlation between the pyranometer connected to the DSS and the outdoor illuminance sensor. The data presented in Figure 12 represent the experimental days during the two stages of the study. The outcomes showed that the regression analysis $R^2$ was 0.99, which indicated a high level of reliability. This finding is significant and indicates a robust validation for the next step.

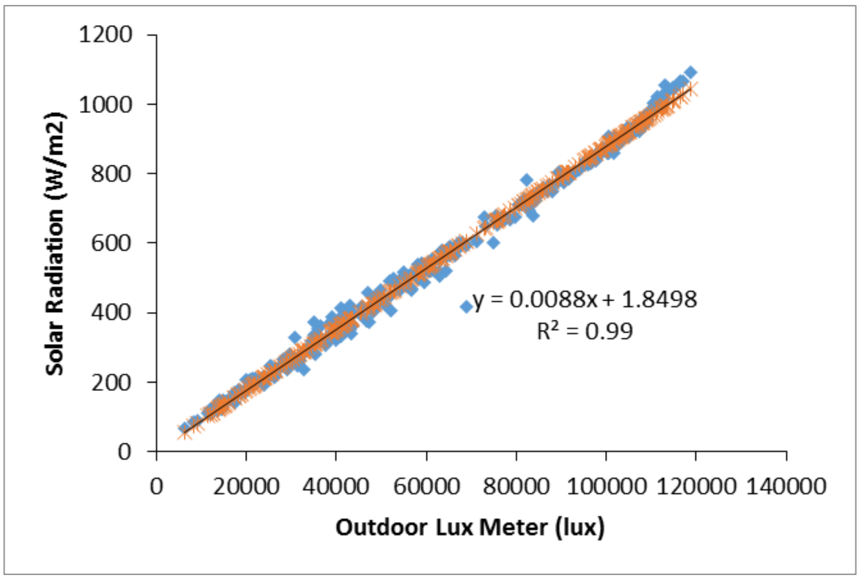



Figure 12: Regression analysis between solar irradiance in DSS and outdoor illuminance in the outdoor stations during the two stages

The second step involved testing the system with one DSS. This step investigated the functionality of the sliding panel and the amount of natural light on the work plane. Figure 13 shows the condition of the outdoor environment during the investigated step; the readings form a bell curve, which reflects the behavior of an intermediate blue sky condition (Munaaim et al., 2014b) with a nebulosity index of 0.81< 0.95. The findings showed that the maximum outdoor illuminance was 109325 lux at 12:40 and the maximum solar irradiance was 955 W/m$^2$. Figure 14 shows the condition of daylight levels on the work plane (800 mm). The DSS was active based on the reading of the photocell under the sliding panel when the pyranometer readings were over 500 W/m$^2$, as shown in the shaded area in Figure 14. When the DSS was below 500 W/m$^2$ and both skylights were opened, the readings from the indoor illuminance sensors were stable and similar, but not identical, due to the movement of the sun and the position of light beam.

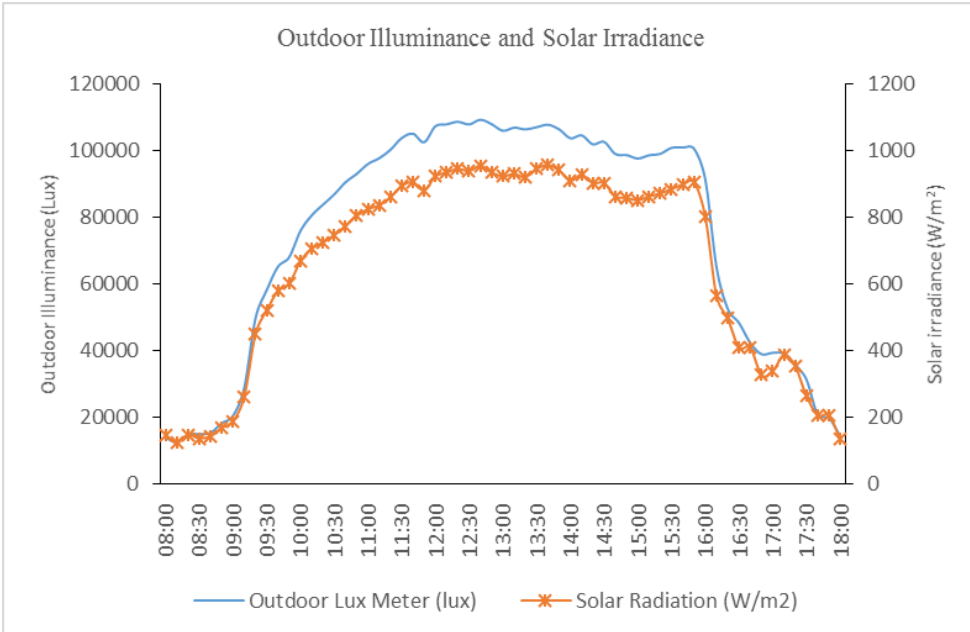



Figure 13: Outdoor condition for Step 2 (Stage 1); measuring outdoor illuminance and solar irradiance

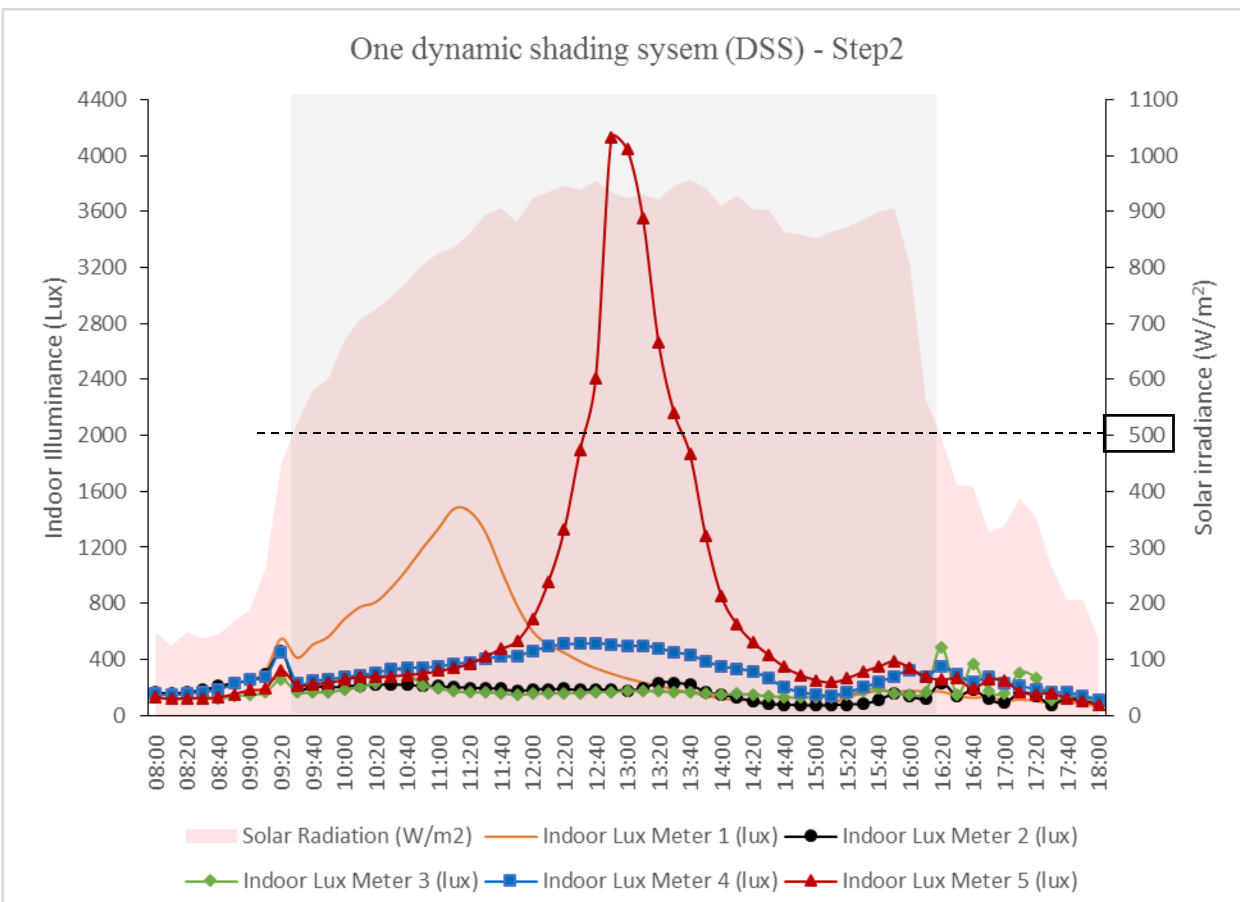



Figure 14: Testing the functionality of one DSS and the acceptability of the illuminance levels

However, when one DSS was active, as shown in the shaded area in Figure 14, the readings of the sensors fluctuated, which indicated the uneven distribution of illuminance on the work plane due to the location of the opened SL. The location of the sensors under and near the opened SL varied significantly and reached a maximum of 4126 lux at 12:50 for Sensor no. 5, 1477 lux at 11:10 for Sensor no. 1, and 516 lux at 12:40 for Sensor no. 4. However, the readings of the other sensors (i.e., nos. 2 and 3), which were far from the opened SL and under a DSS, were more stable, and the maximum records were below 400 lux (Figure 14). This analysis indicates that allowing one SL (1 m × 0.5 m) to be active for a full day can provide high illuminance levels, uneven uniformity, and inhomogeneous illumination on the work plane.

In Step three, the system was tested under intermediate sky condition with a nebulosity index of 0.23<0.70, which represents the common sky condition in the Malaysian environment in a year. This step tested the daylight condition when both DSSs were active and non-active. It aimed to achieve total darkness when the system was active and over 500 W/m$^2$ and to ensure the reliability of the proposed DSS for the second stage. Figure 15 shows the actual outdoor condition for the investigated step, where readings fluctuated in the morning and afternoon. The findings indicated that the maximum outdoor illuminance was 115009 lux at 13:00 and the maximum solar irradiance was 1046 W/m$^2$. However, the sky was cloudy between 14:00 and 16:00, and maximum outdoor illuminance dropped to an average of approximately 40000 lux while solar irradiance dropped to 300 W/m$^2$. Figure 16 shows the condition of daylight levels on the work plane. The readings from the sensors were zero when the DSS was active under both SLs, which indicated total darkness. However, illuminance levels fluctuated with a similar pattern when solar irradiance was below 500 W/m$^2$ due to the location of the sensors and the position of the SLs. This step pointed out that daylight levels were lower than 2000 lux when the SLs were opened and solar irradiance was below 500 W/m$^2$.

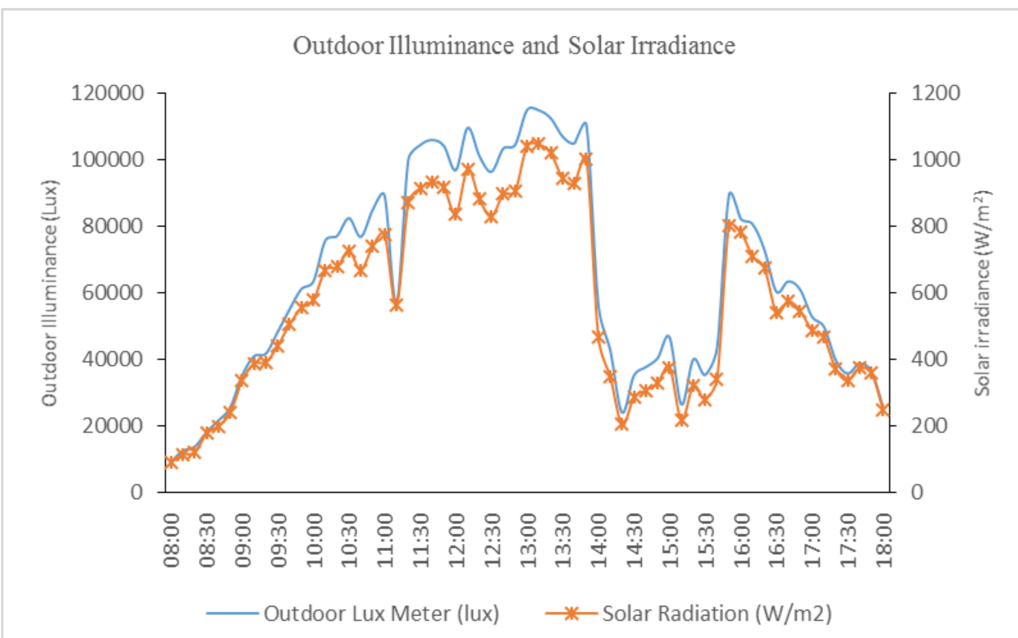



Figure 15: Outdoor condition for Step 3 (Stage 1), i.e., measuring outdoor illuminance and solar irradiance

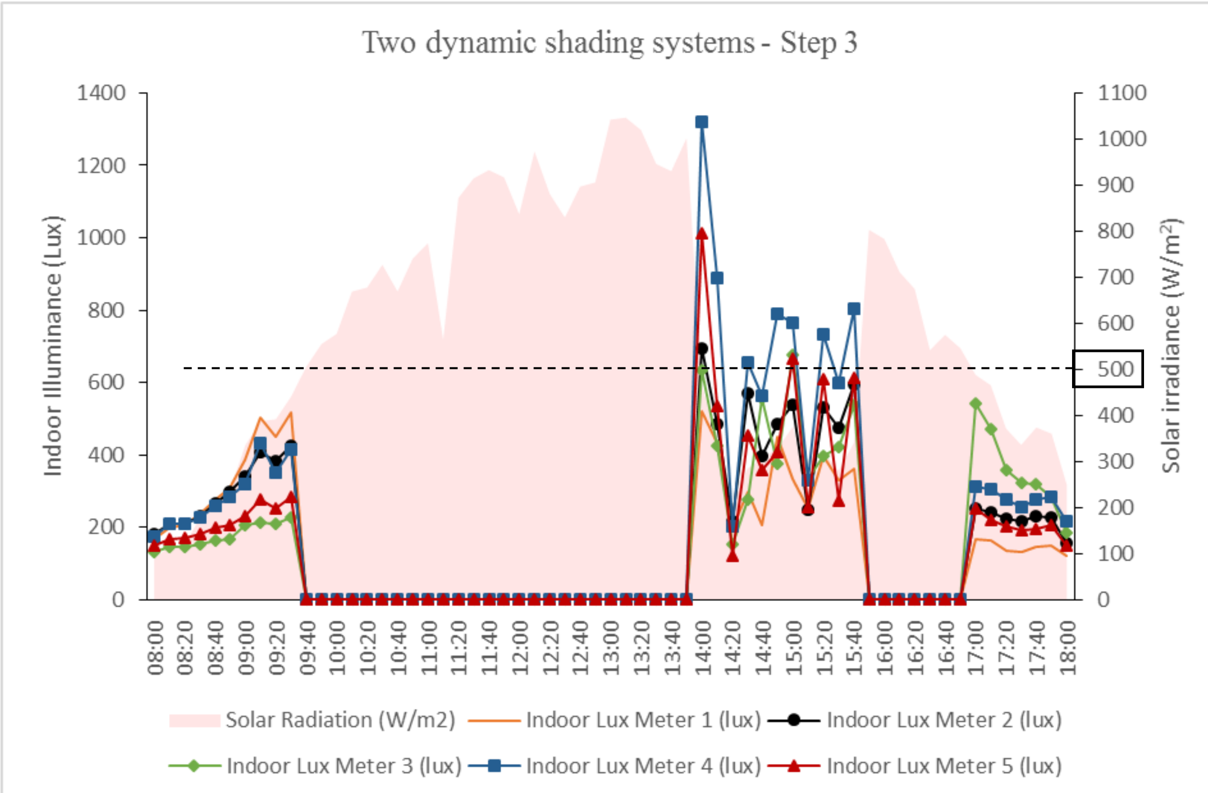



Figure 16: Testing the functionality of two DSSs to achieve total darkness and the acceptability of the illuminance levels

### 4.2. Second stage (integrated daylighting system)

The second and final stage investigated the daylight condition in an indoor environment with the integrated daylighting system. This section presents the performance of the system in three days, which represent an intermediate sky condition, i.e., the most common type of sky condition in this region. Figure 17 shows the condition of the outdoor environment during the three days. The condition clearly indicated that the maximum outdoor illuminance could exceed 110000 lux and solar irradiance of 1000 W/m$^2$ at specific times, particularly between 12:00 and 14:00. Moreover, a significant fluctuation of the readings could occur within a short period. The cloud cover started after 12:00, which resulted in the instability of the sky condition. This situation will presents an issue if the system relies on only one approach or technique. Therefore, the integrated daylighting system was tested under this type of sky condition to specify its efficiency.

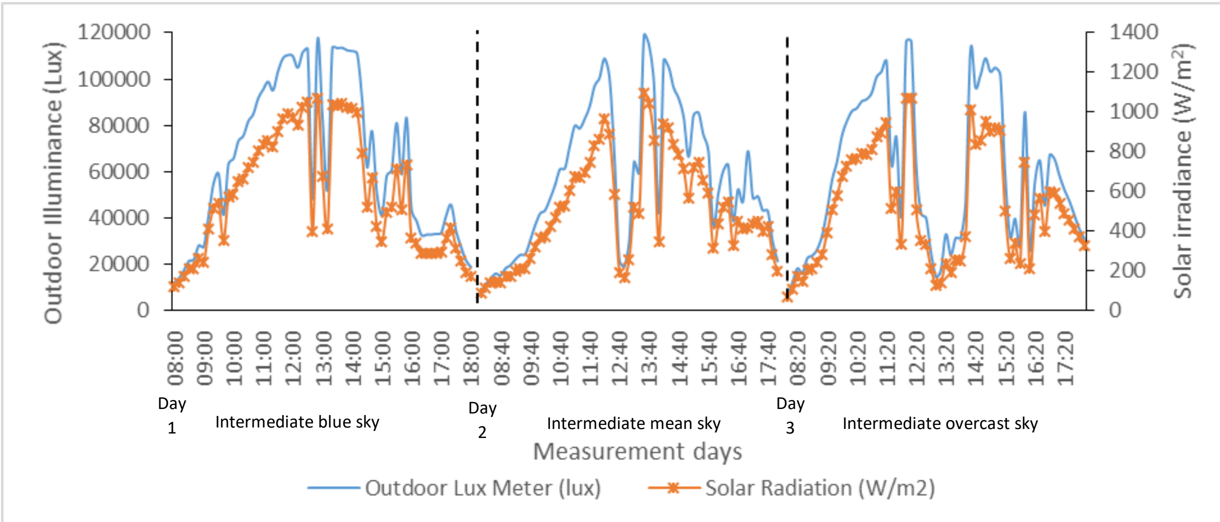
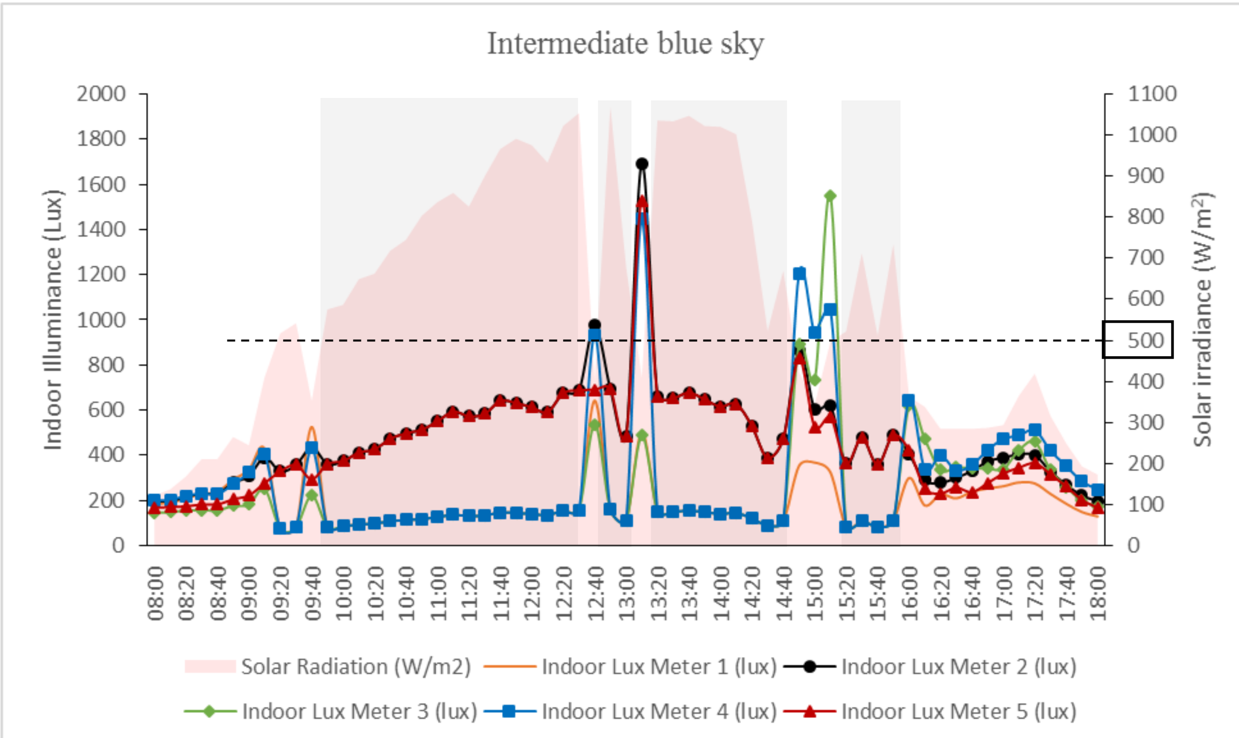


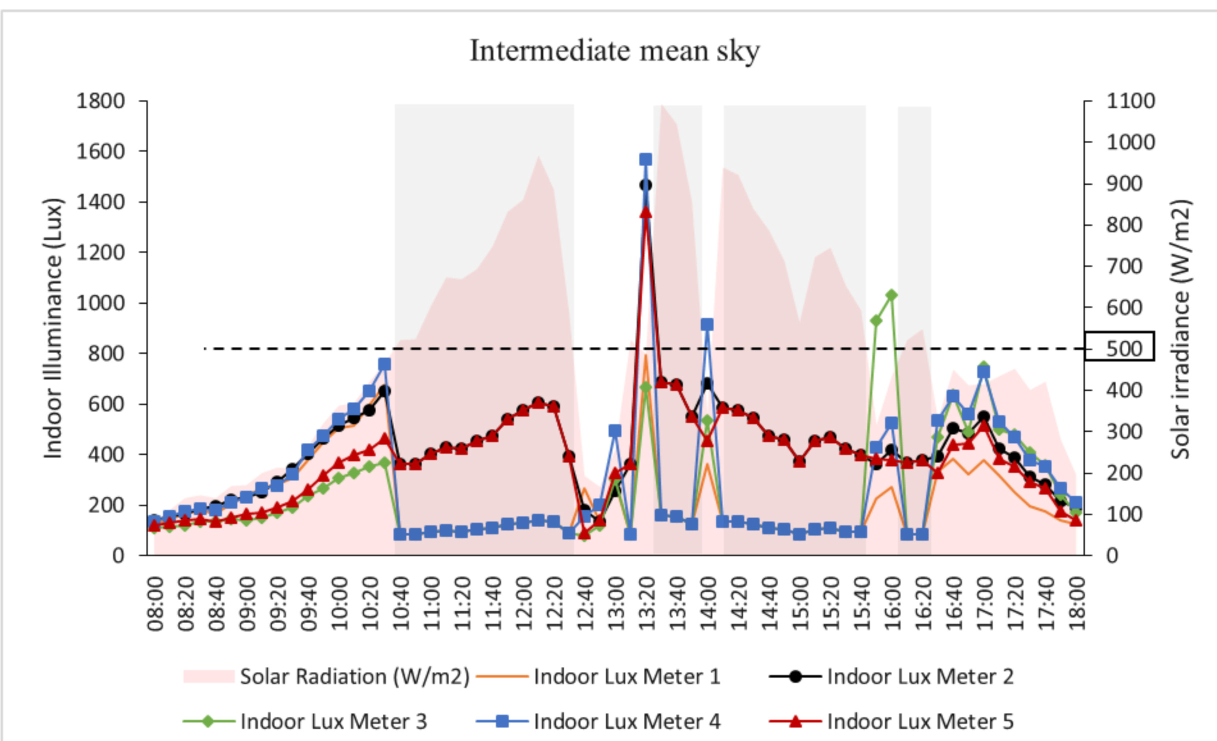

Figure 17: Outdoor illuminance and solar irradiance for three days in March and April (Stage 2)

Figure 18 shows the performance of the proposed system under intermediate sky conditions, such as intermediate blue, intermediate mean, and intermediate overcast, as specified by Zain-Ahmed (2002). The condition of the sky was evaluated based on the nebulosity index models of Baker et al. (2013), Zain-Ahmed (2002), and Munaaim et al. (2014b). Figure 18(a) shows the performance of the system under intermediate blue sky. FODS functioned for a long period, as shown in the shaded area in the figure. When the level of solar irradiance was over 500 W/m$^2$, the DSSs were active, and the indoor daylight sensors delivered uniform illuminance levels. The maximum illuminance was recorded at 694 lux for Sensors 2 and 5 under the diffusers and 159 lux for Sensors 1, 4, and 5 (between two diffusers) when outdoor solar irradiance was 1066 W/m$^2$ at 13:50. The average values were 535 lux (Sensors 2 and 5) and 122 lux (Sensors 1, 4, and 5), which were obtained during operation time. FODS functioned at 54% during daylight hours from 8:00 to 18:00. The SLs were completely visible when the DSSs were non-active, with a solar irradiance below 500 W/m$^2$. The readings for indoor illuminance formed a similar pattern but with different levels due to the locations of the opened SLs and light beam. The maximum reading for illuminance was 1691 lux when solar irradiance was 407 W/m$^2$ at 13:10. The average daylight level obtained from the SLs was 380 lux. The SLs functioned at 46% during daylight hours from 8:00 to 18:00.

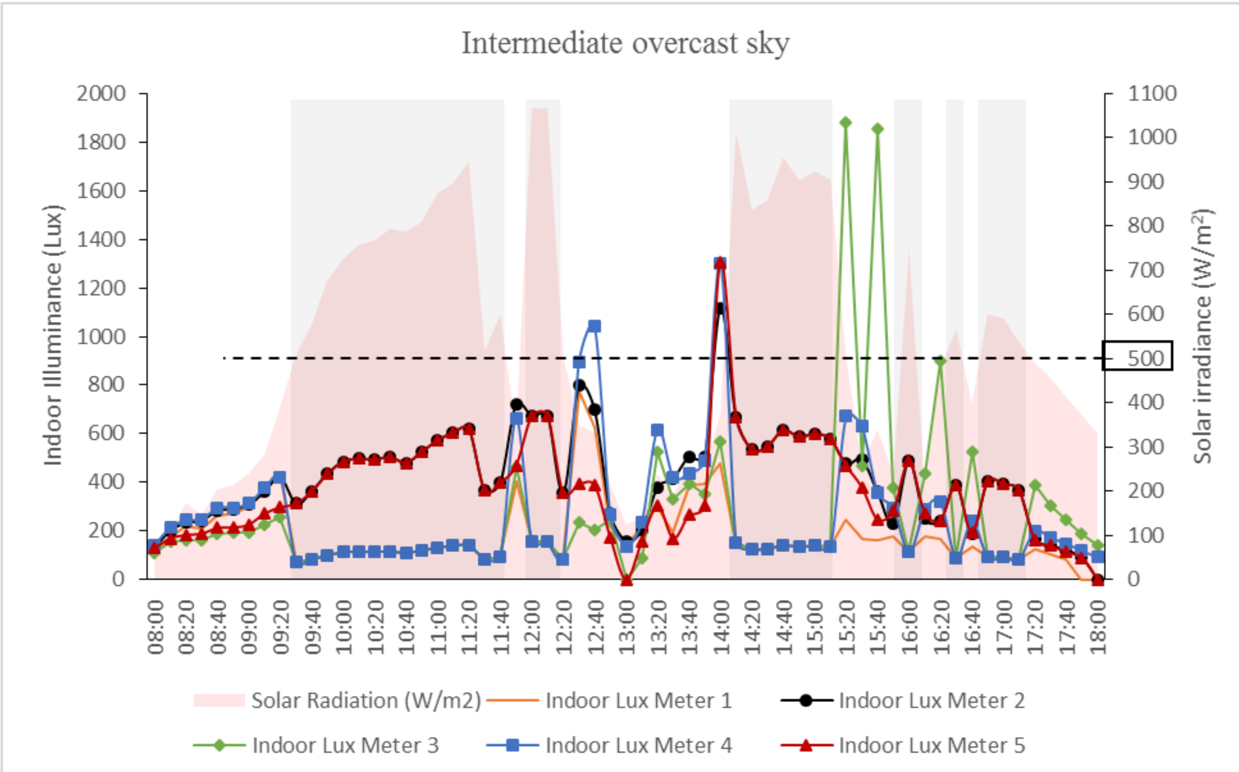
Figure 18 (b) shows the readings for the intermediate mean sky condition. FODS functioned for a shorter period compared with the SL system. The DSSs were active when solar irradiance level was over 500 W/m$^2$. The indoor daylight sensors delivered uniform levels of illuminance. The maximum illuminance was recorded at 689 lux for Sensors 2 and 5 (under the diffusers) and 158 lux for Sensors 1, 4, and 5 (between two diffusers) when outdoor solar irradiance was 1093 W/m$^2$ at 13:30. The average values obtained during the operation time were 478 lux (Sensors 2 and 5) and 110 lux (Sensors 1, 4 and 5). FODS functioned at 46% during daylight hours from 8:00 to 18:00. However, the SLs were completely visible when the DSSs were non-active, with solar irradiance below 500 W/m$^2$. The readings of the indoor illuminance formed a similar pattern but with different levels due to the location of the opened SL and light beam. The maximum reading for illuminance was 1567 lux when solar irradiance was 488 W/m$^2$ at 13:20. The average level of daylight obtained from the SLs was 357 lux. The SLs functioned at 54% during daylight hours from 8:00 to 18:00.




(a) Low cloud cover (intermediate blue)




(b) Moderate cloud cover (intermediate mean)

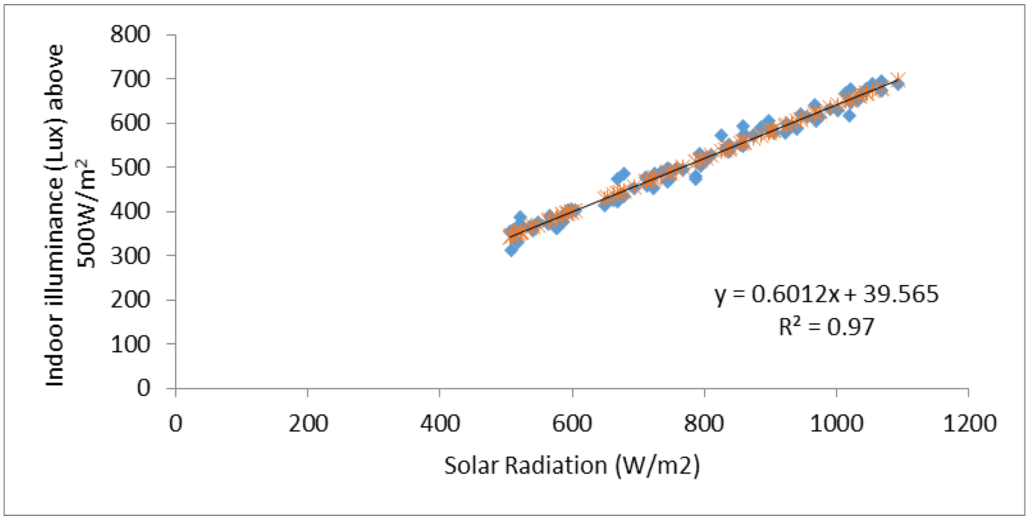



(c) High cloud cover (intermediate overcast)

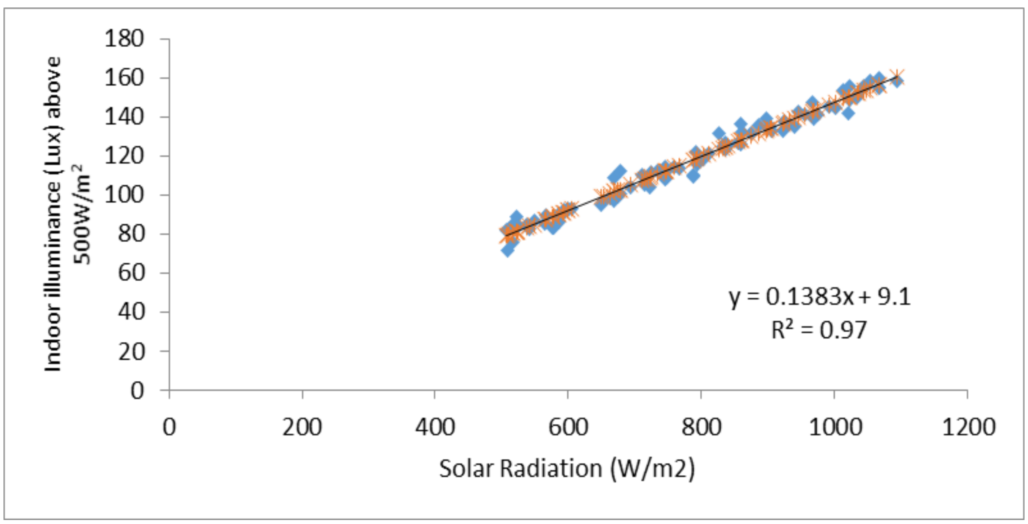
Figure 18: Performance of the integrated daylighting system under three types of sky condition

Figure 18(c) presents the readings for the intermediate overcast sky condition. FODS functioned for a shorter period compared with the SL system. The DSSs were less active than in the previous sky conditions. The figure clearly shows that the indoor daylight sensors deliver less uniform illuminance levels. The maximum readings for illuminance recorded from FODS were 674 lux for Sensors 2 and 5 (under the diffusers) and 138 lux for Sensors 1, 4, and 5 (between two diffusers) when outdoor solar irradiance was 1066 W/m$^2$ at 12:10. The average values were 463 lux (Sensors 2 and 5) and 107 lux (Sensors 1, 4, and 5), which were obtained during the operation time. FODS functioned at 44% during daylight hours from 8:00 to 18:00. The SLs were completely visible when the DSSs were non-active with solar irradiance below 500 W/m$^2$. The readings for indoor illuminance formed a similar pattern but with different levels due to the location of the opened SLs and the light beam. The maximum reading for illuminance was 1879 lux for Sensor 3 when solar irradiance was 499 W/m$^2$ at 15:20. The average level of daylight obtained from the SLs was 366 lux. The SLs functioned at 56% during daylight hours from 8:00 to 18:00.

Figure 19 shows the regression analysis of the results obtained from the correlation between the readings of the indoor daylight sensors above 500 W/m$^2$ and the solar irradiance results from the pyranometer for the presented days. This analysis validated the obtained results of FODS from the sensors with two locations: under the diffusers and between the diffusers. The regression model indicates a significant $R^2$, which is 0.97 for the two locations. This result supports and proves the functionality of the DSSs and their application to control the integration between SLs and FODS.




(a) Sensors 2 and 5 under the diffusers




(b) Sensors 1, 3and 4 in the middle of two diffusers and the test cell

Figure 19: Correlation analysis to validate the results of indoor illuminance recorded from FODS: (a) Sensors 2 and 5 under the diffusers and (b) Sensors 1, 3, and 4 between two diffusers

## 5. Discussion

The experimental process of the two stages illustrated the evaluation of the proposed integrated daylighting system for enclosed spaces without access to daylight from side openings. Stage 1 was conducted through three steps. The first step was performed to obtain compatibility for the readings from the pyrnometer in the DSS and the outdoor station, which was extremely high. The regression analysis $R^2$ was 0.99 and provided a stable platform to test the integrated daylighting system. Moreover, the study found that the frequency of obtaining solar irradiance above 500 W/m$^2$ was high and could occur under Malaysian condition. The second step tested the condition of providing one control DSS to test for functionality and one opened SL to test for efficiency. The results found that the DSS could function according to readings above or below 500 W/m$^2$ and provided a controlled environment in certain locations under its position. However, the opened SL offered a high illuminance level in locations under or near its position. The impact of direct sunlight on specific locations exceeded 4000 lux. This step showed that although the size of the opened SL was less than 5% of the total roof area (20 m$^2$), the opened SL disturbed the illuminance uniformity of the work plane. The third step tested and evaluated the functionality of the DSS to provide total darkness in an indoor space when it was closed. This step was performed to validate the results of FODS in the second stage and to evaluate the illuminance level provided by both SLs when the DSS was opened and below 500 W/m$^2$. The readings at this stage confirmed the functionality of the DSS, and the sensors recorded zero illuminance level when the DSS was active and exposed to over 500 W/m$^2$. Moreover, the experiment showed that the daylight levels were controlled, and that the integrated daylighting system recorded readings below 2000 lux when the DSS controlled the opening of the SLs.

The second stage tested and assessed the functionality of combining the three components: SL + TC, DSS, and FODS. The readings obtained under the three typical intermediate sky conditions that represented the common types of sky conditions in Malaysia and collected for 2 months provided evidence for the significant fluctuations of sunlight levels within a short period. Approximately half of the daytime period showed solar irradiance levels below and above 500 W/m$^2$. The outcomes of the outdoor station were reflected on the performance of illuminance in an indoor environment. The integrated daylighting system showed that FODS was able to deliver a sufficient level of natural light, namely, 300–680 lux (under the diffusers) and 75–151 lux (between two diffusers) during the three days. The SLs were controlled by the DSS and delivered a maximum reading below 2000 lux only at a specific time within an average of 350 lux. The functionality of SL + TC and FODS ranged from 48% to 52%. Moreover, the integrated daylighting system delivered more uniform illuminance when solar irradiance was over 500 W/m$^2$, with a maximum reading of below 700 lux.

Table 2 presents the performance summary of the integrated daylighting system. At the end, the research identified several limitations that need to be considered to develop the application of integrated daylighting system such as the location and distribution of FODS, skylight types and shading mechanisms. Understanding the effectiveness of these factors could improve the performance of the proposed system in tropical buildings.

Table 2: Average readings of the integrated daylighting system under three types of sky conditions

<table>
<tr><th colspan="2" rowspan="2">System</th><th colspan="3">Performance</th><th colspan="2">Functionality</th></tr>
<tr><th>Max (lux)</th><th>Mean (lux)</th><th>Min (lux)</th><th>Active</th><th>Non-active</th></tr>
<tr><td colspan="2">Skylights</td><td>1712</td><td>455</td><td>106</td><td rowspan="2">52%</td><td rowspan="2">48%</td></tr>
<tr><td colspan="2">Dynamic Shading system</td><td colspan="3">Moveable panel Close > 500 W/m$^2$<br>Open > 500 W/m$^2$</td></tr>
<tr><td rowspan="2">Fiber Optic daylighting system</td><td>Under diffusers</td><td>685</td><td>492</td><td>329</td><td rowspan="2">48%</td><td rowspan="2">52%</td></tr>
<tr><td>Between diffusers</td><td>151</td><td>131</td><td>75</td></tr>
</table>

## 6. Conclusion

This study presented a new design model for an innovative daylighting system for enclosed spaces without access to daylight from side openings in tropical buildings. The integration of three design models into one platform was effective for the Malaysian built environment. The investigation indicated the capability of the proposed system to perform efficiently during the testing days. The results showed that the integration was functional and the level of natural light was controlled. The integrated daylighting system succeeded in eliminating the need for electrical lighting during daytime. It delivered a dynamic lighting environment with a specific range of illuminance that is acceptable under international standards. The proposed system addresses the problem that occurs in utilizing SLs in low-rise buildings and overcomes the problem of using LED lighting with FODS to deliver a stable and continuous supply of natural light in indoor spaces. The proposed system contributes significantly to knowledge of integrated designs and the behavior of unstructured data produced from daylighting systems in a built environment.

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